Precise Kinematic GPS Processing and Rigorous Modeling of GPS in a Block Adjustment

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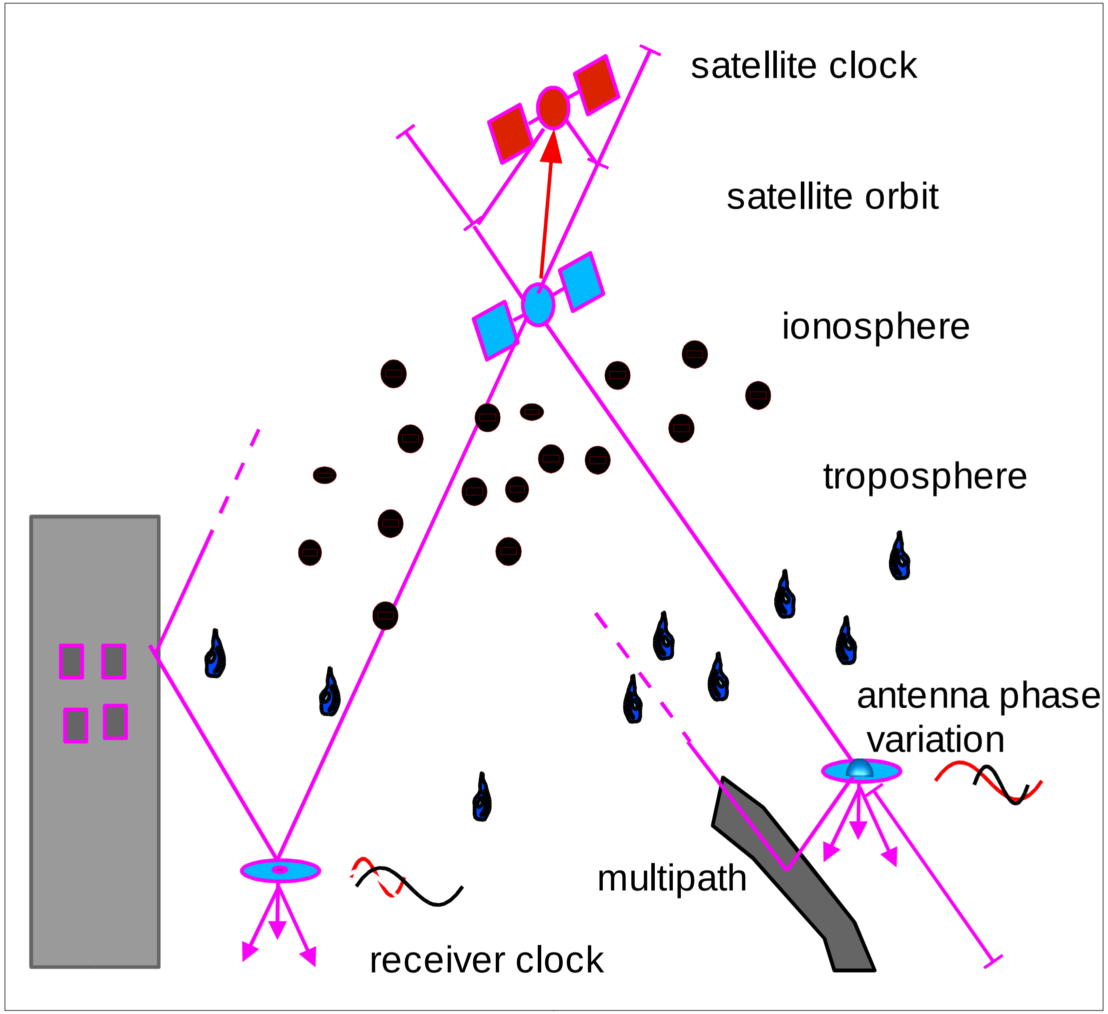
Motivation

- precise kinematic GPS processing
- challenging GPS task
- combination of GPS and photogrammetric applications
- handling of remaining GPS coordinate errors
- generally approximation without reflecting GPS model applied
- rigorous GPS Model developed for combined GPS/block adjustment
- GEONAP-K GPS- / BINGO block adjustment
- operationally applied since 1996
- operational experiences underline advantages

- reconsideration of models required

GPS Error Sources

- **station dependent** error
  - antenna phase variation (PCV)
  - multipath
- **distance dependent** error
  - ionosphere
  - troposphere
  - satellite orbit
- kinematic GPS: **additional** systematic **coordinate effects**
  - constellation changes
  - approximate or false ambiguity resolution



Magnitude of GPS Error Sources

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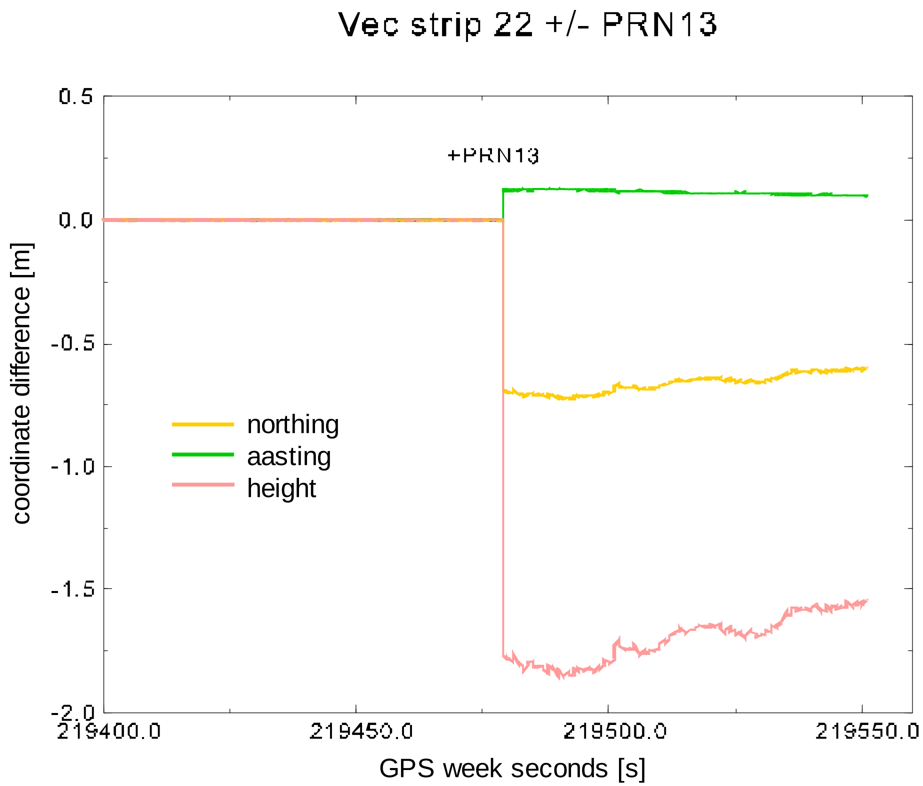
error source	absolute influence	relative influence
satellite orbit	2 ... 50 m	0.1 ... 2 ppm
clock	2 ... 100 m	0.0 ppm
ionosphere	0.5 ... >100 m	1 ... 50 ppm
troposphere	0.01 ... 0.5 m	0 ... 3 ppm
multipath code	m	m
multipath phase	mm ... cm	mm ... cm
antenna	mm ... cm	mm ... cm

(green) high spatial correlation — (red) local (calibration)

Systematic GPS Coordinate Errors

- systematic GPS coordinate errors may be present due to
  - false ambiguity fixing (time dependent effects)
  - changes in the satellite constellation (discontinuity)
  - GPS error sources
- magnitude of errors depends on
  - geometric GPS conditions (DOP values)
  - known systematic GPS effects
- modeling of these errors attempted in combined adjustment of GPS and aerial triangulation



Modeling of Kinematic GPS

Kinematic GPS Processing	***local reference station***	***remote reference station***	***reference station network***
ambiguity resolution	possible	difficult	possible
distance dependent errors:			
• ionosphere	ignore,estimate, eliminate	ignore,estimate, eliminate	estimate, eliminate
• troposphere	model, estimate	model, estimate	model, estimate
• orbit	BE, PE	BE, model, PE	BE, model, PE
remaining systematic effects:			
• shift, drift of coordinates	approximate, rigorous model	approximate, rigorous model	approximate, rigorous model
• antenna PCV	correct	correct	correct
costs	high	low	low

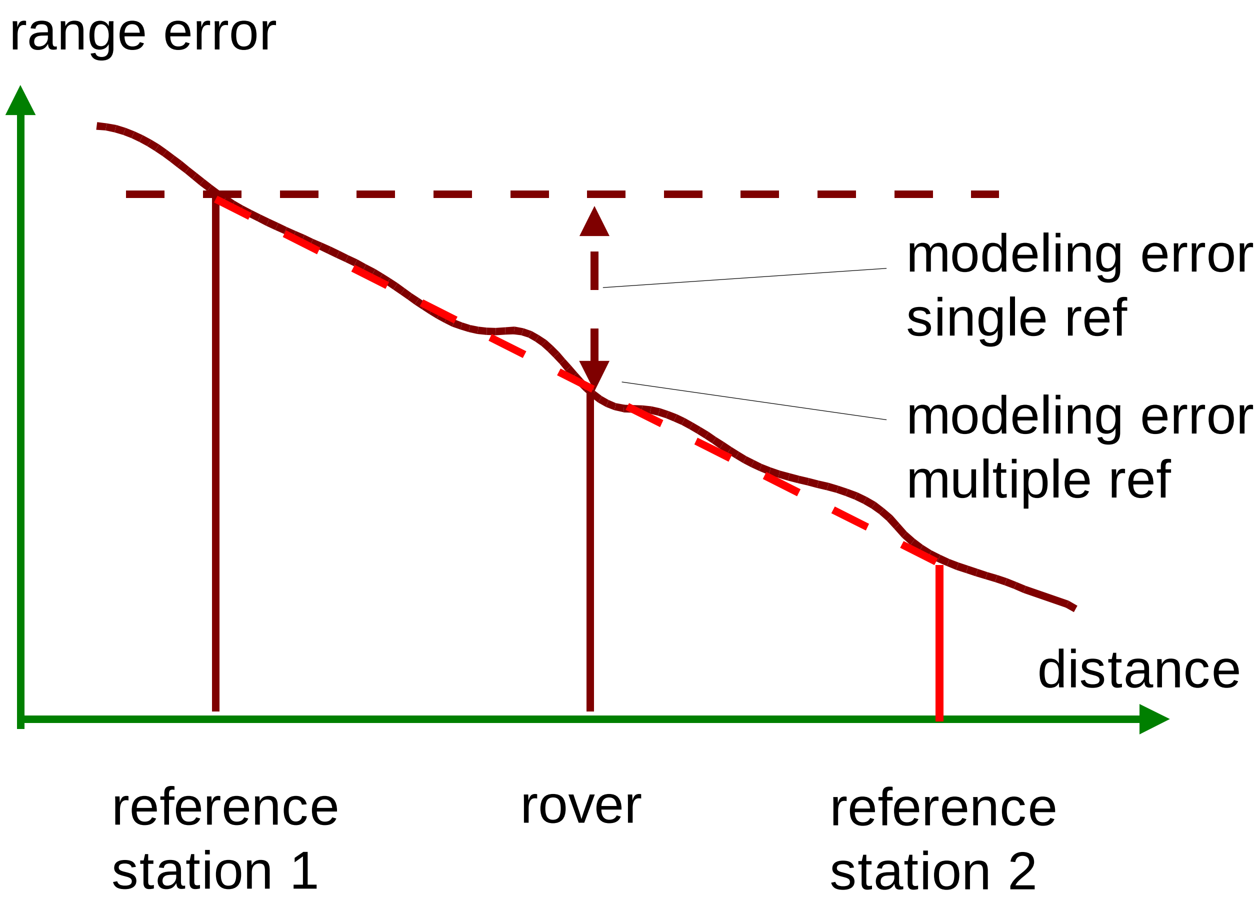
- all major effects can be corrected or modeled
- consider costs for choice on reference station(s)

▬ recommended, but depends very much on application and data

BE broadcast ephemeris
PE precise ephemeris
PCV phase (center) variations

Distance Dependent GPS Errors

- spatial correlation of GPS errors
- distance dependency
- advantage to use multiple reference stations
- allows better modeling of GPS errors



Geo++® GEONAP

- GEONAP – since 1988
  - *Geo*detic *Na*vstar *P*ositioning
  - **multi-signal**, **multi-station**, multi-session adjustment (rigorous adjustment of different signals and multiple kinematic and/or static stations)
  - **undifferenced observable** with **complete variance-covariance estimation**
- development and maintenance of GEONAP by *Geo*++® - since 1990
- advanced GPS software
  - for static and kinematic applications
  - for small, large and regional applications
  - different accuracy levels from mm ... m

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DGPS

- trajectory with **dm ... m** accuracy
- precise navigation applications
  - **no ambiguity resolution** necessary
  - use of code observations
  - carrier-phase smoothed code observations

PDGPS

- trajectory with **cm ... dm** accuracy
- precise positioning applications
  - **ambiguity resolution** required
  - simultaneous adjustment of kinematic and reference station data
  - several kinematic and/or reference stations possible

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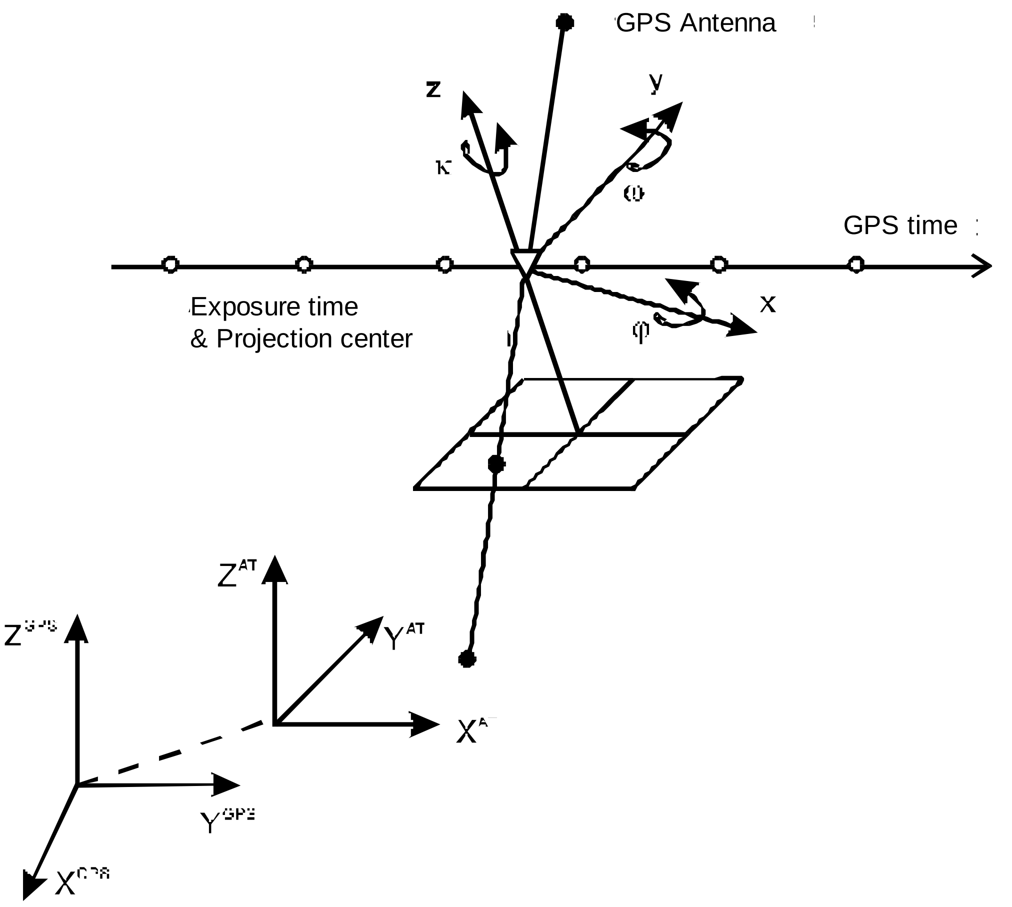
- application for **photogrammetric application**
- **sophisticated feature**: subsequent processing with

  GEONAP-K package for GPS data and
  BINGO for combined adjustment

- only operationally applied **rigorous GPS modeling in block adjustment**
- also termed CPAS (Combined Phase Ambiguity Solution)

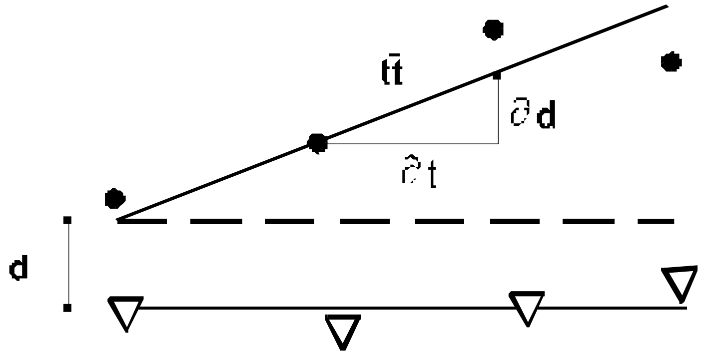
Relating GPS and Aerial Triangulation

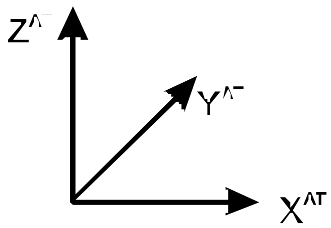
- pre-requisite: unchanged or known conditions of antenna/camera for the complete photo-flight
  - **identical reference point** by orientated vector antenna/camera
  - **identical reference time** by interpolation of GPS coordinates or synchronization of GPS and camera
  - **identical geodetic datum** by datum transformation and/or adjustment



Shift- and Drift- Approximation in GPS/Block Adjustment

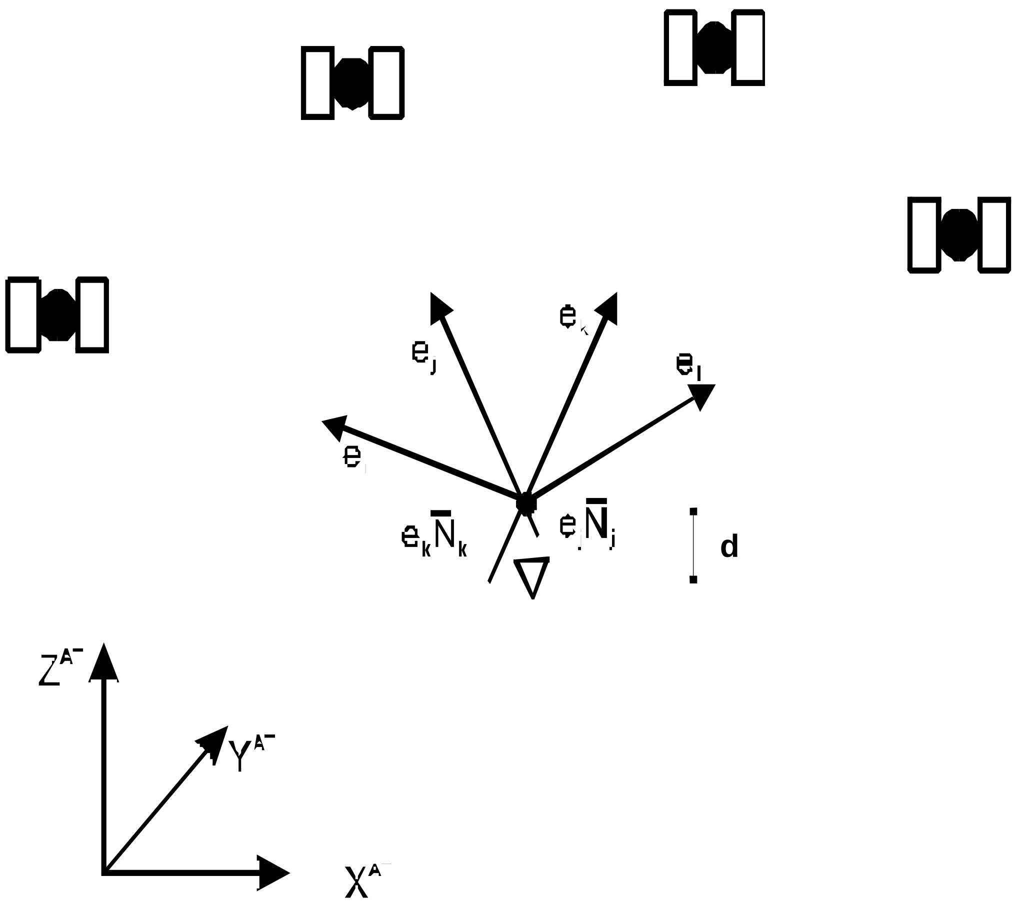
- projection center ● GPS and ∇ AT
- functioning of the shift- and drift-parameter
  - translation and time/strip dependent corrections
    - generally for every strip
    - individual for coordinate components
    - no relationship between strips by GPS
    - considers no changes of satellite constellation
    - approximation of actual GPS model





Rigorous GPS Model in GPS/Block Adjustment

- projection center ● GPS and ∇ AT
- functioning of rigorous GPS modeling
  - unreliable ambiguities / constellation changes
    - considers actual GPS satellite constellation
    - estimates range/position correction
    - keeps geometric GPS relationship
    - reduces correlation with other parameter



Comparison of the Mathematical Models

- rigorous GPS model

$$X_{P\ i}^{AT} = X_{A\ i}^{GPS} + dX_D + (QA^T P)_i * \bar{N}_i + R_i(\phi \omega \kappa) * dX_A$$

- shift and drift approach

$$X_{P\ i}^{AT} = X_{A\ i}^{GPS} + dX_D + (dSP_i) + R_i(\phi \omega \kappa) * dX_A$$

$X_{P\ i}^{AT}$	coordinates of projection center
$X_{A\ i}^{GPS}$	(interpolated) coordinates GPS antenna
dX_D	datum transformation
$QA^T P_i$	GPS design information
$\bar{N}_i$	ambiguity/range term
$R_i(\phi \omega \kappa)$	rotation matrix from block adjustment/IMU
dX_A	vector GPS antenna/projection center
dSP_i	shift & drift parameter term
i	photo i

Interface between GPS and Block Adjustment

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- complete design-information accessible by elevation e and azimuth a of the GPS satellites

$$\boldsymbol{A_j} = \begin{bmatrix} a_1 \\ a_2 \\ \dots \\ a_k \end{bmatrix} \qquad a_k^T = \begin{bmatrix} e_x \\ e_y \\ e_z \\ c_0 dt \end{bmatrix} = \begin{bmatrix} -\cos e \cos \alpha \\ -\cos e \sin \alpha \\ -\sin e \\ 1 \end{bmatrix}$$

- book keeping of GPS ambiguities N (wavelength λ)

$$\bar{N}_i = \begin{bmatrix} \bar{N}_1 \\ \bar{N}_2 \\ \dots \\ \bar{N}_k \end{bmatrix} = \lambda \cdot \begin{bmatrix} N_1 \\ N_2 \\ \dots \\ N_k \end{bmatrix} \qquad N_k = \begin{cases} 0 & \text{reliable fixed} \\ 1 & \text{not reliable fixed} \end{cases}$$

- estimation of coordinate correction in combined adjustment

$$\boldsymbol{dX_i} = (\boldsymbol{QA^T P}_i) * \boldsymbol{\bar{N}}_i$$

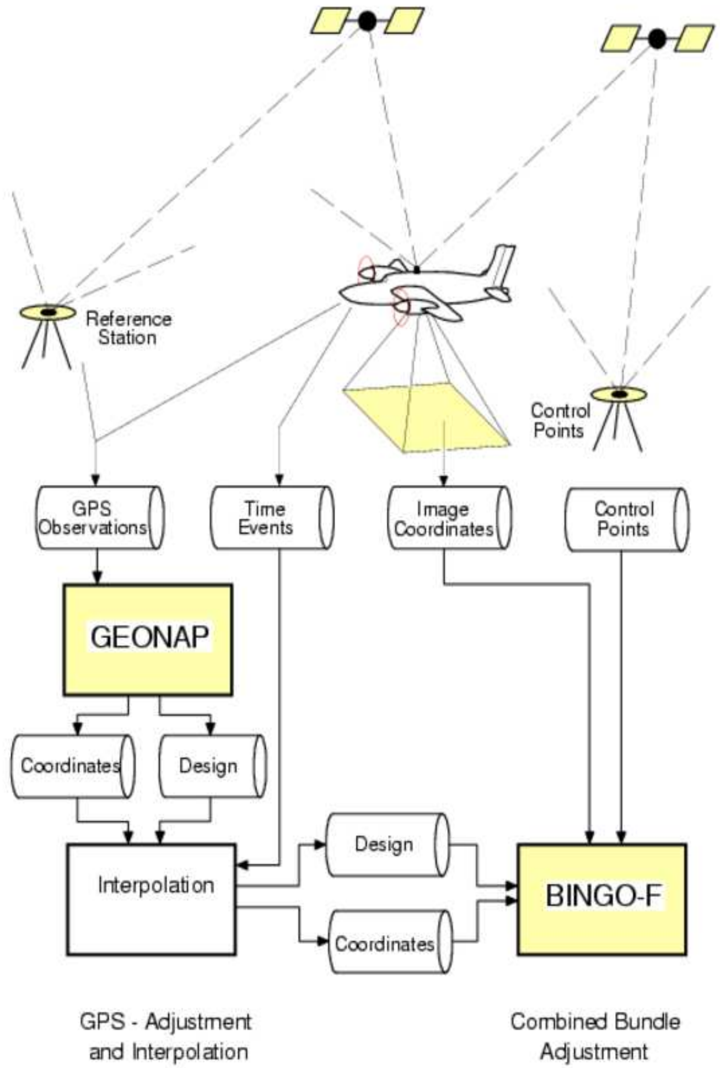
Benefits of Rigorous Modeling of GPS

- correct modeling of all GPS errors
- independent of strips/block
- considers the actual GPS model
- considers time dependent effects and GPS constellation changes
- reduced number of unknowns
- relative accuracy of GPS coordinates is maintained (for all strips and complete block)
- no crossing strips required
- separation of systematic GPS errors from
  - e.g. datum parameters
  - additional parameters e.g. interior orientation
- reduction of ground control points and side lap possible
- cost reduction feasible

Data Flow GEONAP/BINGO

- standardized precise kinematic GPS processing
- provides trajectory of kinematic GPS antenna
- provide design information and ambiguity status for every event
- not necessary to solve all ambiguities
- coordinate transformation

- complete information to rigorously model GPS in block adjustment



Summary

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- precise kinematic GPS processing revisited
  - all major error components can be corrected or modeled
  - advantages of multiple reference stations

- rigorous GPS modeling in combined GPS/block adjustment revisited
  - uses the actual GPS satellite geometry
  - advantages and benefits of approach
    - keeps geometric GPS relationship / strengthening of geometry in block adjustment
    - correct functional GPS model / reduced correlation with other parameter

- operational procedure with GEONAP-K and BINGO since 1996 for publications on the presented topic refer also to

www.geopp.com

or directly to

http://www.geopp.com/publications/english/lit_e.htm